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Wear and friction behaviour of high-speed steel and indefinite chill material for rolling ferritic stainless steels

Abstract

In this paper, wear and friction behaviour of high-speed steel (HSS) and indefinite chill (IC) material for rolling a ferritic stainless steel were investigated on a tribometer. A disk specimen of the ferritic stainless steel-B445J1M was pre-oxidised at 1100 °C for 30 min, and then rotated against a pin at 500 °C for 30 min. The pin was made of HSS or IC material. It was found that the friction coefficient of the IC was lower than that of the HSS, but the mass loss of the HSS pin was less than that of the IC pin. The oxide scale of the disk was more easily worn out and attached on the HSS pin than that of the IC pin.

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Wear and friction behaviour of high-speed steel and indefinite chill materials for work rolls

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Abstract: The wear mechanism of work rolls is of importance for developing roll materials and improving surface quality of rolled products. In the present paper, friction and wear behaviour of high-speed steel (HSS) and indefinite chill (IC) materials for work rolls were investigated on a tribometer. A disk specimen of ferritic stainless steel-B445J1M, pre-oxidised at 1100 °C for 30 min, then rotates against a pin at 500 °C for 30 min, in which the pin is made of HSS or IC roll. It is found that the friction coefficient of IC is lower than that of HSS. The abrasion of the HSS is less severe than that of the IC and the substrate of disk when the HSS pin was used is more likely to expose.

Keywords: Friction; wear; high-speed steel; indefinite chill roll; hot rolling.

1. Introduction

The properties of work rolls essentially help strip manufacturers to fulfill the increasing demand for improved strip surface finish, tight dimensional tolerances and higher productivity [1, 2]. Recently, three types of roll materials are widely used, namely high chromium (Hi-Cr) steel, high-speed steel (HSS) and indefinite chill (IC) materials [3]. The development of HSS in the early 1990s enabled high chromium rolls to be progressively substituted in the early finishing stands of hot strip mills. However, it could not be successfully achieved by replacing IC rolls with HSS in the later stands [4, 5]. Because the numbers of cobbles, double folded strip and tail end pinches increase in the later stands of a hot strip mill, mechanical cracks seem to grow

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deeper in HSS than that in IC rolls [6]. Moreover, during the hot rolling of stainless steels, it is also reported that the sticking defects are obviously improved with the application of IC rolls, since the graphite in the IC materials can retard crack propagation and reduce friction [7-9]. Consequently, a general recommendation is thus to use HSS rolls primarily in former stands, whereas IC rolls are applied in later stands, which has been adopted in hot rolling mills worldwide [10].

Due to the complex operating conditions during hot rolling, it is quite difficult to evaluate tribological properties of work rolls on-line. As a result, pilot testers have been used to simulate the operating conditions in hot rolling. Vergne *et al* [11, 12] studied the interaction between the oxides on a work roll grade and a strip steel on a pin-on-disk configuration at elevated temperatures. Kato *et al* [13] investigated mechanisms of the surface deterioration of roll for hot strip rolling on a two-disk hot wear rig. Lundberg *et al* [14] found that the main wear mechanism in hot-work tool-steel rolls is abrasion, and steel rolls are not suitable in rolling at 900 °C on a high-temperature test rig. Hanlon *et al* [15] investigated the wear response of both conventionally cast and spray cast materials using a Cameron-Plint multi-purpose friction and wear testing machine configured for rolling/sliding contact tests.

In the current work, the wear behaviour of the HSS and the IC rolls was investigated on the basis of a pin-on-disk tribological tester, in which the pin represents the HSS or IC rolls while the disk represents a ferritic stainless strip. The aim is to compare the wear behaviour of the HSS and the IC rolls by analysing the influences of their microstructural characteristics on mass loss, wear track and friction coefficient.

2. Materials and experimental procedure

2.1 The materials

In this study, a Rtec tribometer with a pin-on-disk configuration was set up at an elevated temperature. The pin consists of work rolls (HSS and IC) and the disk represents a typical ferritic stainless steel (B445J1M) usually suffering sticking defects. The chemical compositions of the pin and the disk materials are listed in Table 1. The HSS contains a high amount of strong carbides former elements, such as V, Cr and Mo. The volume percentage of carbides mainly

depends on the specific composition and solidification conditions [16]. The IC material shows a higher C than that of the HSS, existing in the form of graphite and cementite M_3C ($M=Fe, Cr$), whereas B445J1M contains high content of Cr (21.5%) and no Ni, revealing excellent resistance to oxidation and corrosion and low cost [17].

Table 1. Chemical compositions of the pin and disk materials (wt%)

Material	C	V	Cr	Ni	Mo	Si
HSS	2.1	4.4	4.5	0.32	4.9	0.7
IC	3.35	-	1.85	4.54	0.49	0.77
B445J1M	<0.01	-	21.5	0.0	0.6	0.3

2.2 Experimental procedure

The disk was machined to a cylinder with the dimensions of 50 mm in diameter and 5 mm in height, and then metallographically ground by means of SiC papers up to 1200 grit, while the pin was cut into a cylinder with a 3 mm radius hemispherical end. The basic configuration of the pin-on-disk tribometer is shown in Fig. 1.

Tribological tests were carried out in three steps: (a) the disk was heated up to 1100 °C in a furnace for 0.5 h, forming a layer of oxide scale about 2.2 μm ; (b) after the pre-oxidation, the disk was heated up to 500 °C by a high frequency induction in the tribometer chamber. As the desired temperature reached, the disk was held for 20 min to equilibrate; and (c) the pin, applied a normal load of 10 N equal to 1.42 GPa of the maximum Hertz contact stress, was brought into contact with the pre-oxidised disk and the sliding was started at a linear sliding speed of 0.1 m/s for a total period of time 30 min. In order to verify the reproducibility of the results, each test was conducted at least twice.

The conditions selected for the present wear test were mainly determined by the limits of the laboratory experimental apparatus. These might be different from those in real rolling practice. However, the present wear test can be used to compare the wear behaviour of different roll materials [18-20].

Fig. 1 Schematic view of pin-on-disk tribometer

3. Results and discussion

3.1 Microstructures

The microstructures of the investigated materials are shown in Fig. 2. The HSS (Fig. 2a) contains a large amount of carbides, which can be distinguished by different contrasts and morphologies, namely the dark slender petal-like zones are V-rich MC carbides, white long regions are Mo-rich M_2C carbides and the grey zones are Cr-Fe-rich M_7C_3 carbides [21]. Image analysis of its BSE image reveals that the total area fraction of these carbides is 12.5%, including 8.5% MC and 4.0% M_7C_3 and M_6C . In addition, there are three different phases (Fig. 2b), graphite, cementite (Fe_3C) and tempered martensite in the IC [7], comprising 4.3% graphite and 20.8% cementite. The HSS has a high hardness of 760 HV whereas the IC has a lower hardness of 633 HV.

Fig. 2 Microstructures of the HSS (a) and the IC (b)

3.2 Friction

Fig. 3 shows curves of friction coefficient of the tribological tests under a normal load of 10 N, a linear sliding speed of 0.1 m/s and a temperature of 500 °C. It is evident that the friction coefficient of IC is lower than that of HSS. The friction coefficient started at a relatively high static friction coefficient (~ 0.8 for HSS and ~ 0.7 for IC), then suddenly dropped to a minimum value (~ 0.4 for HSS and ~ 0.35 for IC), afterwards, kept comparatively stable. The friction coefficient reached stable in a short time, approximately 120 s for HSS and 180 s for IC, and the average friction coefficients were 0.47 and 0.39 for HSS and IC, respectively. According to curves of friction coefficient, the tests can be subdivided into 2 stages: (i) the first stage corresponds to rapid drop of friction coefficient until stabilisation; and (ii) the second stage reveals the stabilisation of the friction coefficient.

Fig. 3 Curves of friction coefficient versus sliding time

3.3 Wear

Laser scanning image and 3D profile of the wear track on the disk when the HSS pin was used are shown in Fig. 4a and b, respectively. This is a typical feature observed on the whole wear track of the disk. Three different contrasts are observed in Fig. 4a, namely bright white marked “A”, less bright marked “B” and dark areas. Combined with the 3D profile of the track in Fig. 4b, it is found that bright white zones correspond to high positions, while less bright zones to the lower position. In addition, EDS spectra of “A” shown in Fig. 4c suggests the constituents of the HSS. Therefore, the bright white zones should be the detached debris from the HSS pin. The less bright zones are extensively grooved, indicating the oxide scale in these areas was worn out and substrate exposed. Moreover, the dark areas in the wear track display that the abraded oxide scale still exists in these areas.

Fig. 4 Laser scanning image (a) and 3D profile (b) of the wear track tested by the HSS pin and EDS spectra of “A” in (a)

Similarly, the characteristics of the wear track when IC pin was applied can be concluded. Three different contrasts in Fig. 5a, bright white marked “A”, less bright marked “B” and dark areas correspond to the detached debris of the IC pin, the substrate of the disk and the abraded oxide scale. The constituents of the bright white “A” in Fig. 5a are confirmed by its EDS spectra (Fig. 5c). Compared with Fig.4a, white black areas in Fig. 5a are greater than that in Fig. 4a, while less bright areas in Fig. 5a are less than that in Fig. 4a, revealing that the abrasion of the HSS is less severe than the IC and the substrate of disk when the HSS pin was used is more likely to expose.

Fig. 5 Laser scanning image (a) and 3D profile (b) of the wear track tested by the IC pin and EDS spectra of “A” in (a)

Before and after tests, both pins were ultrasonically cleaned in alcohol to determine the mass loss using a high precision balance (0.1 mg). The mass loss of the HSS pin (0.3 mg) is less than that of the IC pin (0.7 mg). In addition, the diameters of the HSS and IC pin track are approximately 1182 and 1252 μm, respectively. All the evidences further confirm that the HSS is more wear resistant than that of the IC, in good agreement with the results of rolling mills and that obtained by other authors in similar laboratory tests [22, 23]. The wear rate was correlated with hardness, because the HSS (760 HV) is harder than that of the IC (633 HV).

Fig. 6 shows the 3D profile and cross section of the disk after the oxidation. It is seen that the surface of the oxide scale (Fig. 6a) is made up of complicated asperities [24], and when the pins are brought into contact with the disk, the nodules on the disk first contact with the pins and then abrade. After the oxidation of the disk at 1100 °C for 30 min, the average thickness of the oxide scale reaches at 2.2 μm (Fig. 6b). Cheng *et al* [17, 25] found that the main composition of the oxide scale for B445J1M (disk material) is Cr₂O₃. Therefore, the initial friction contact is established between the oxide scale on the disk and the metal on the pin.

Fig. 6 3D surface profile (a) and cross section (b) of the disk after the oxidation

In the case of unsteady conditions, the general evolution of the friction coefficient can be associated with the abrasion of the oxide scale. The interrupted tests were performed to observe the wear phenomena. Because the friction coefficients (Fig. 3) stabilise approximately 120 s for HSS and 180 s for IC, two interrupted pin-on-disk tests were conducted, representing the initial point of stabilisation for the HSS and IC pins, respectively. Fig. 7 shows laser scanning image and 3D profile of the wear track tested by the HSS pin which terminated at 120 s since the start of the test. According to the friction coefficient curve in Fig. 3, it is the start of stabilising the friction coefficient for the HSS pin. It can be seen that nearly all the substrate in the wear track exposed and its 3D profile was severely grooved.

Fig. 7 Laser scanning image (a) and 3D profile (b) of the wear track tested by the HSS pin after the tribological test for 120 s

Fig. 8 shows laser scanning image and 3D profile of the wear track tested by the IC pin which terminated at 180 s since the start of the test, corresponding to the start of stabilising the friction coefficient for the IC pin. The morphology of the wear track in Fig. 8 is quite different from that in Fig. 7. Apart from the exposure of the substrate (“B” in Fig. 8a), the IC debris (“A” in Fig. 8a) is also attached in the wear track.

Fig. 8 Laser scanning image (a) and 3D profile (b) of the wear track tested by the IC pin after the tribological test for 180 s

Fig. 9 presents schematic model of wear mechanism for HSS pin and IC pin at each stage, respectively. At the initial of the test (Fig. 9a), contact between the pin and the disk is considered as a metallic pin on an oxidised disk. When the pin is put on the disk, the disk rotates against the pin tip. The pressure initially is so high, and the oxide scale is swiftly worn out. At the first stage, the HSS pin contains a certain amount of carbides and exhibits high hardness [26, 27]. Therefore, the oxide scale on the disk rapidly abrades, exposing the substrate in the wear track (Fig. 9b). As the pin-on-disk test continues, the diameter of the worn top of pin increases and the contact pressure correspondingly decreases. With the accumulation of the abraded oxide scale and detachment of the HSS, the substrate, the oxide scale and the debris of the HSS are eventually observed in the wear track. However, the IC pin has a considerable amount of graphite and this graphite plays a role of lubrication [6, 28]. Accordingly, the friction coefficient of the IC pin is

lower than that of the HSS pin in Fig. 3. As the rotation continues, the disk creeps under loading and the contact surface of the pin becomes circular. As the contact area between the pin and disk increases, the Hertz contact pressure reduces, and the oxide scale is less easily worn out. Because of the softer IC material, the debris of the IC pin is more apparently attached to the wear track (Fig. 9b' and c'), and the diameter of the top of worn IC pin (D_{II}) is greater than that of the HSS pin (D_{HI}) in Fig. 9c'. The adhesion and abrasion can contribute to the wear mechanism of both rolls.

Fig. 9 Schematic model of wear mechanism for HSS pin (a) (b) (c) and IC pin (a') (b') (c')

4. Conclusion

High temperature pin-on-disk tests have been carried to investigate the wear behaviour of the HSS and the IC rolls. The evolution of the friction coefficient during the pin-on-disk tests can be divided into 2 stages, namely the rapid decrease of the friction coefficient and stabilisation stage. The results show that the friction coefficient of IC is lower than that of HSS. The interrupted tests reveal that the oxide scale is swiftly worn out. In addition, the HSS is more wear resistant than that of the IC. However, more areas of the substrate expose when the HSS pin is used, following the higher possibility of sticking during the hot rolling of the ferritic stainless steel.

Therefore, in order to improve sticking for hot rolling of ferritic stainless steels, it is further confirmed that HSS rolls should be applied in the early stands of hot strip mills, while IC rolls employed in the later stands.

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